HOW DO SUPRA-THERMAL RUNAWAY ELECTRONS AFFECT THE RETURN CURRENT/NONTHERMAL BEAM DYNAMICS IN SOLAR FLARES?

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Implications of study

Implications for thermal response

(1) Return currents heat corona faster to higher temperatures, BUT heat chromosphere slower and to lower temperatures

(2) Ambient plasma can become dominated by supra thermal electrons=> need kinetic treatment of ambient plasma

(3) The heating by the return current is reduced by the presence of runaway electrons but it is higher than heating by Coulomb collisions

Implications for the acceleration region

(1) Suprathermal runaway electrons return to the acceleration region, if the acceleration is ongoing

(2) Nonthermal seed particles are present in the corona to be further accelerated to high energies

OUTLINE

Introduction: Do we have a handle on the low- and high-energy cutoffs?

Return currents affect the observationally deduced electron power and energy cutoffs

- Assumptions of runaway return current model
- Example of RADYN calculation with and without return currents (Runaways negligible)
- Comparison of cases with and without runaways

Summary and future work

DO WE HAVE A HANDLE ON THE LOW- AND HIGH-ENERGY CUTOFFS?

Yes! In flares with strong observed flattening ("breaks") at lower energies during main impulsive phase

(50% of M- and X-class flares 2002-2006: Alaoui, Krucker, Saint-Hilaire 2019)

Strong X-ray flattenings inconsistent with all known propagation effects (Alaoui & Holman 2017)

Strong flattenings inconsistent with observable (Holman 2003) high-energy cutoffs < 1 MeV because flare emission above the background is observed to MeV range in 13/18 flares

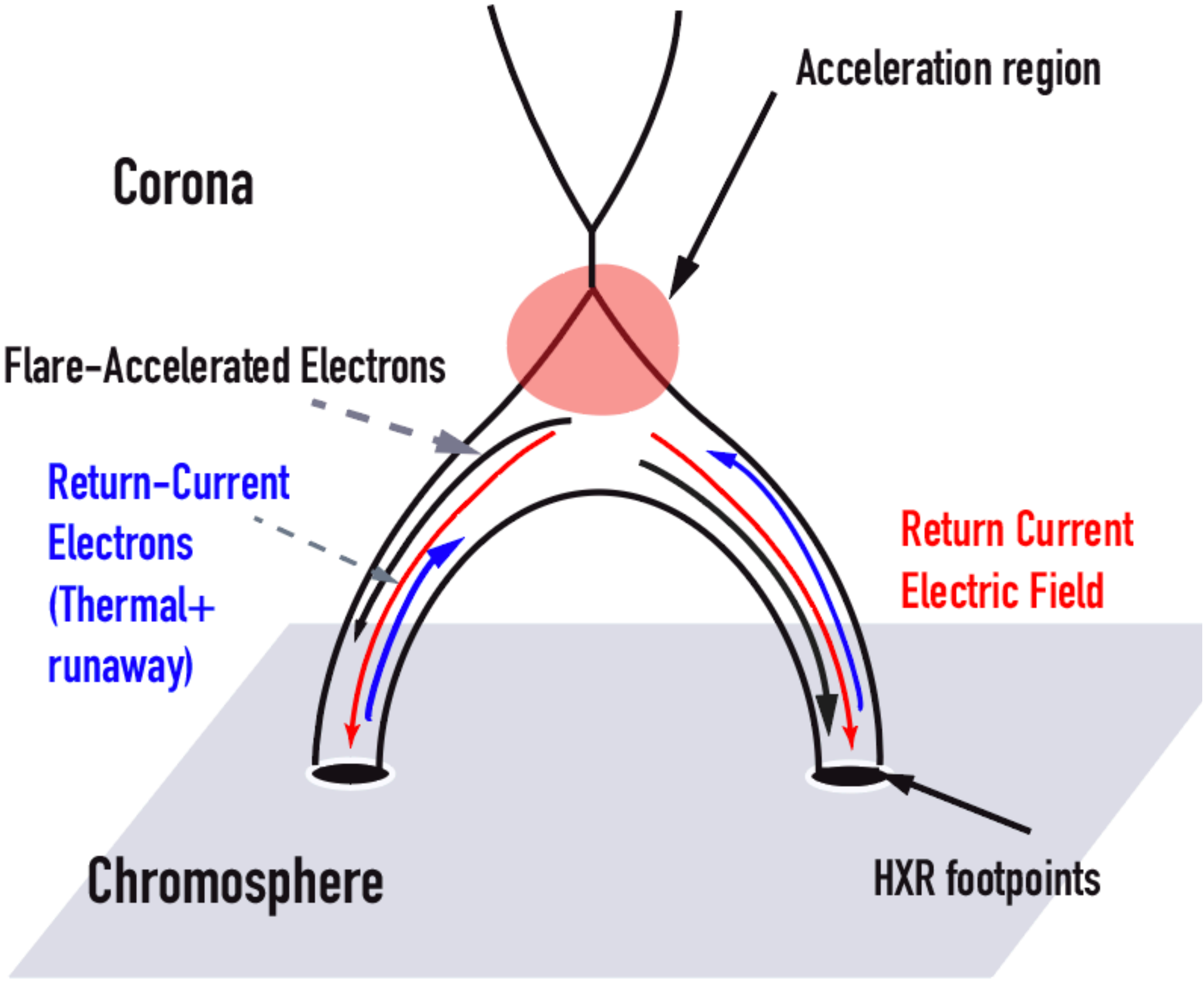
=>Low-energy cutoffs necessary to explain the **strong** flattenings of main impulsive phase
(Time evolution and goodness of fit favor gradual rather than sharp low-energy cutoffs)
Alaoui & Holman 2017

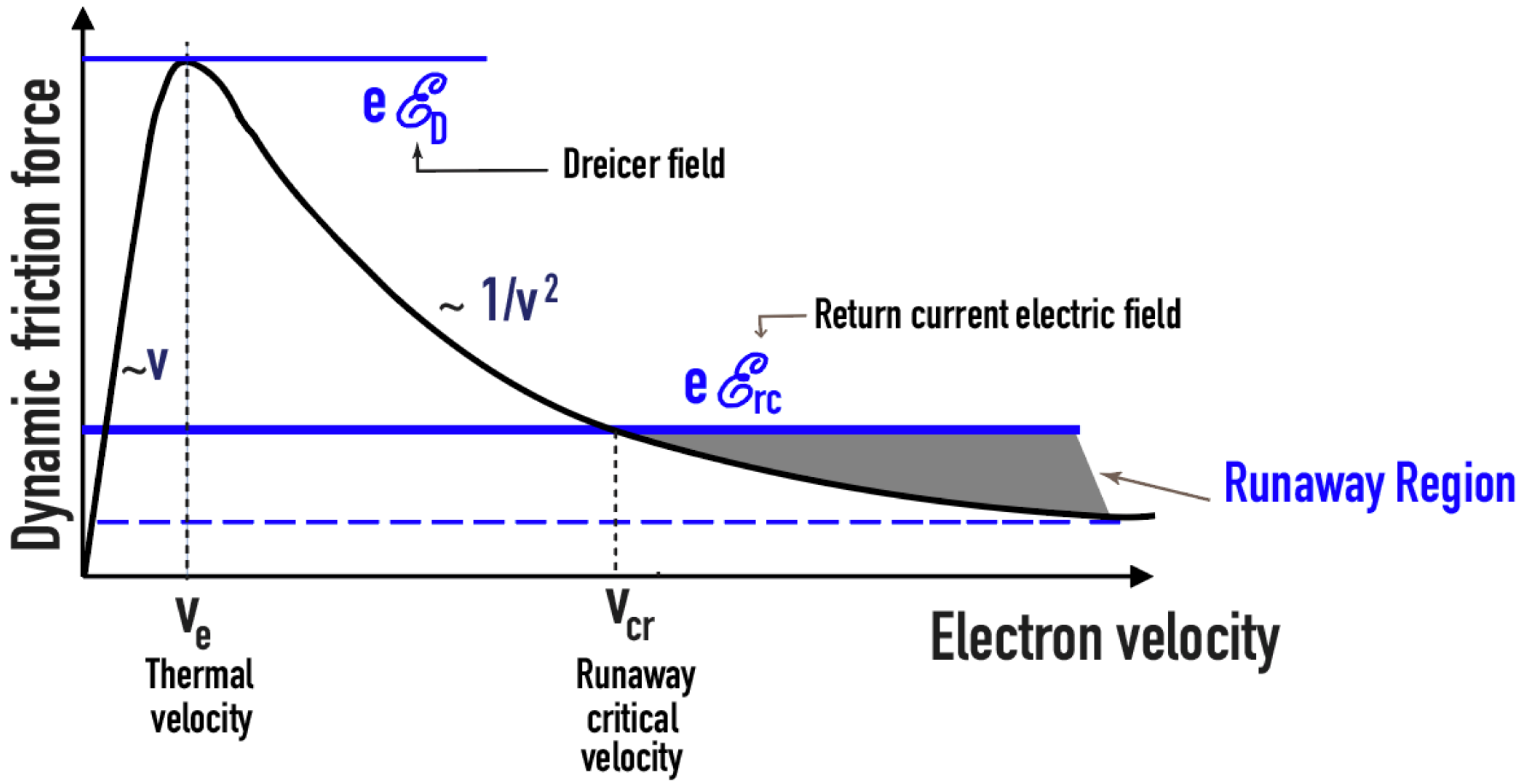
Yes! In 6 events, with strong flattenings during the late impulsive phase

Warmuth et al 2009: An event with low-energy cutoffs >100 keV during the last peak of impulsive phase

Other events: Low-energy cutoffs higher than 70 keV consistent with 6 late peak RHESSI events:
(Alaoui et al. in prep, cf. SPD 2021 poster)

EXTENDED STANDARD MODEL WITH RETURN CURRENTS





MODEL DESCRIPTION: FIND ELECTRIC FIELD ASSUMING

POWER-LAW INJECTED accelerated electrons continuously injected at apex of 1D loop model

CURRENT BALANCE

$$J_{beam}(x) = J_{RC}(x)$$

$$\longrightarrow J_{drift}(x) + J_{runaway}(x)$$

Ohm's law

Runaway growth rate from Landreman et al. (2014)

STEADY-STATE Time scales >> than electron-ion collision time, i.e. return current/beam system reached steady-state (Van den Oord 1990)

STABLE RETURN CURRENT No current-driven instabilities. Resistivity is Spitzer

SUB-DREICER ELECTRIC FIELD $E_{RC} < 0.12 E_D$ everywhere along the electrons' path

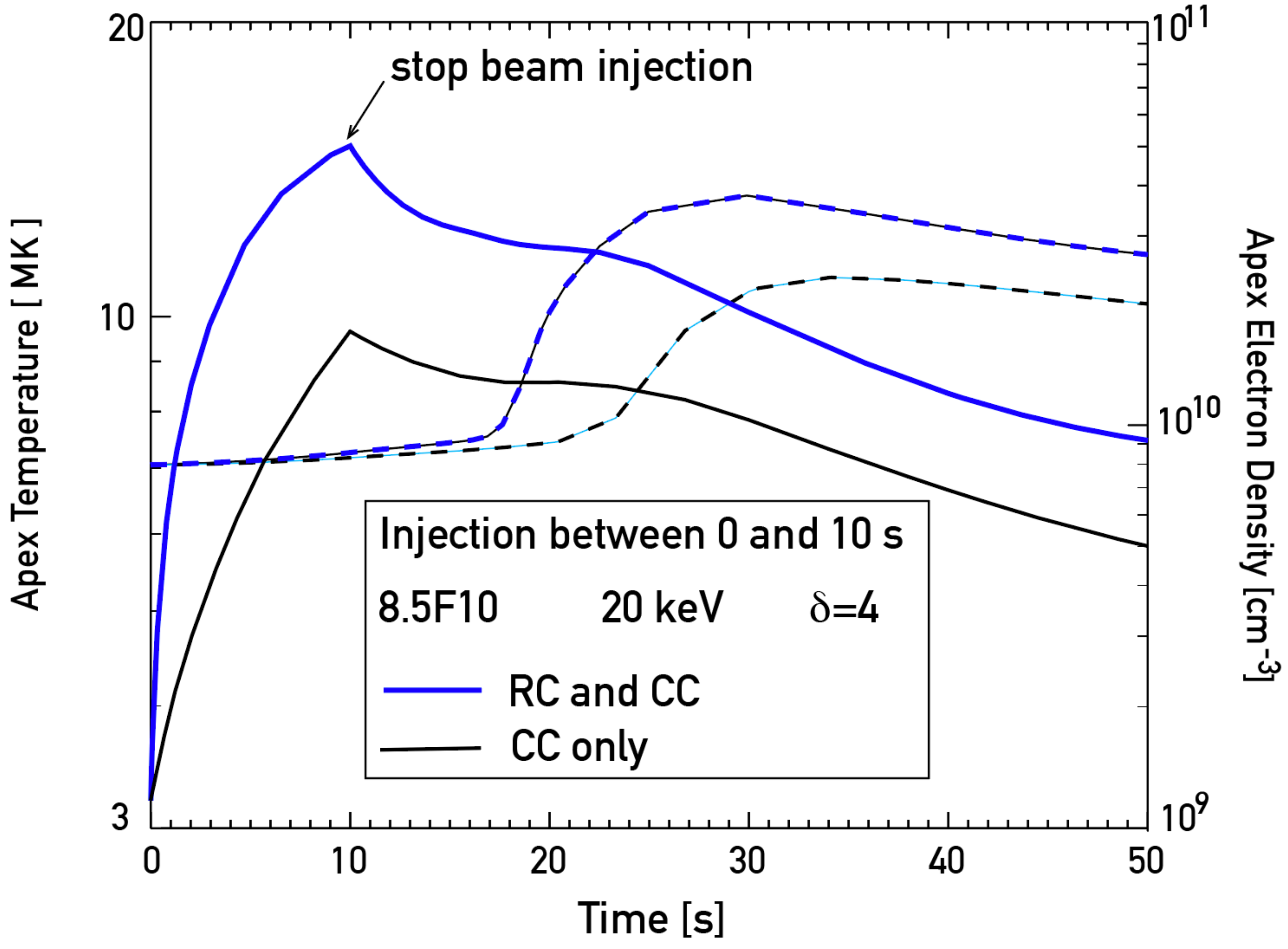
We use higher values for E_{RC} but the accuracy of the solution decreases with increasing E_{RC}

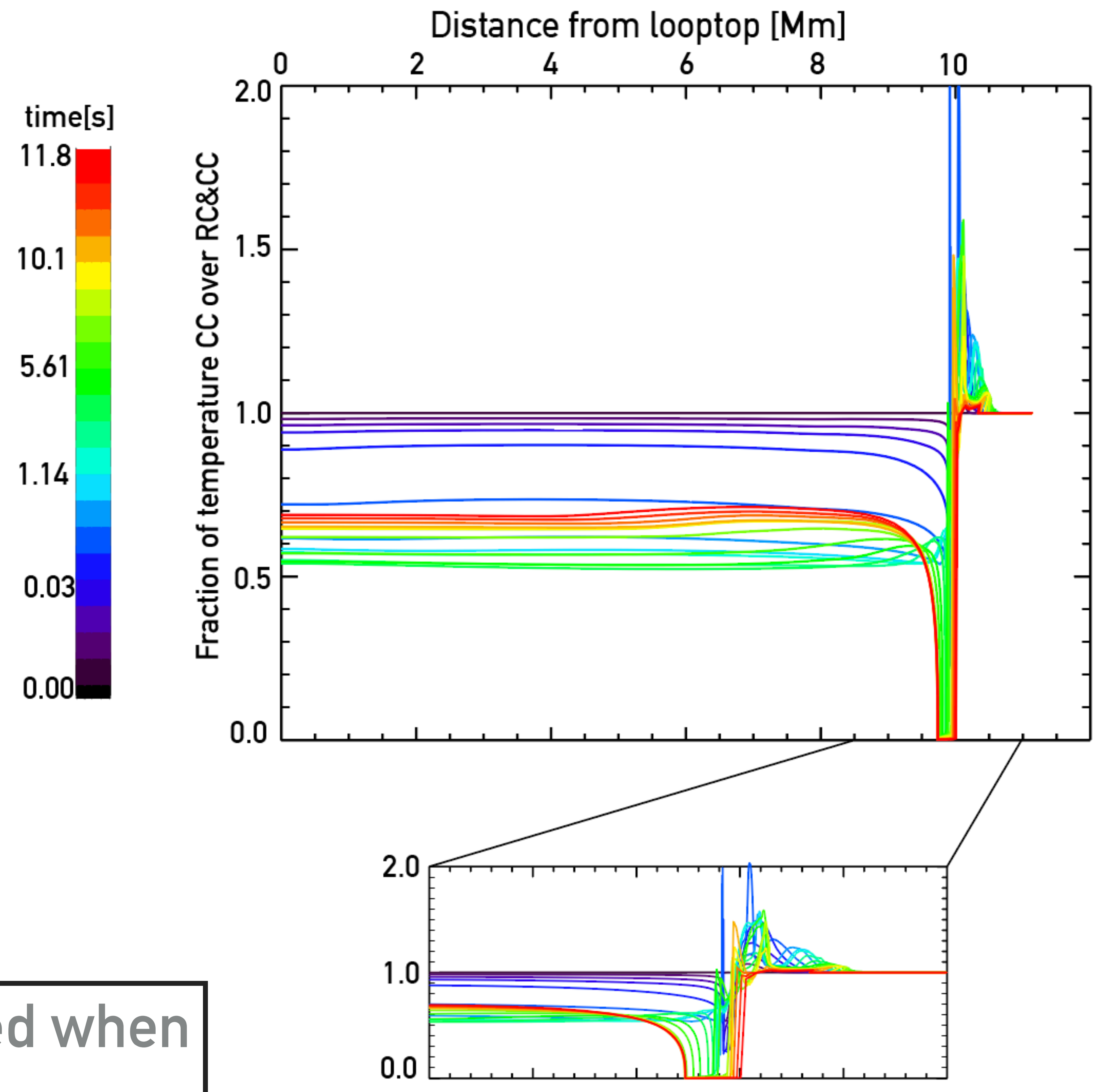
THERMALIZATION OF ELECTRONS If energy of direct beam electrons reaches thermal energy, electrons lost from beam

RETURN CURRENTS HEAT CORONA FASTER AND TO HIGHER TEMPERATURES

In this example, runaway electrons are ~3% at the looptop, so we use FP (Allred+20) with & without return current

Observationally, if return currents are not considered,
Injected electron and energy flux densities are overestimated

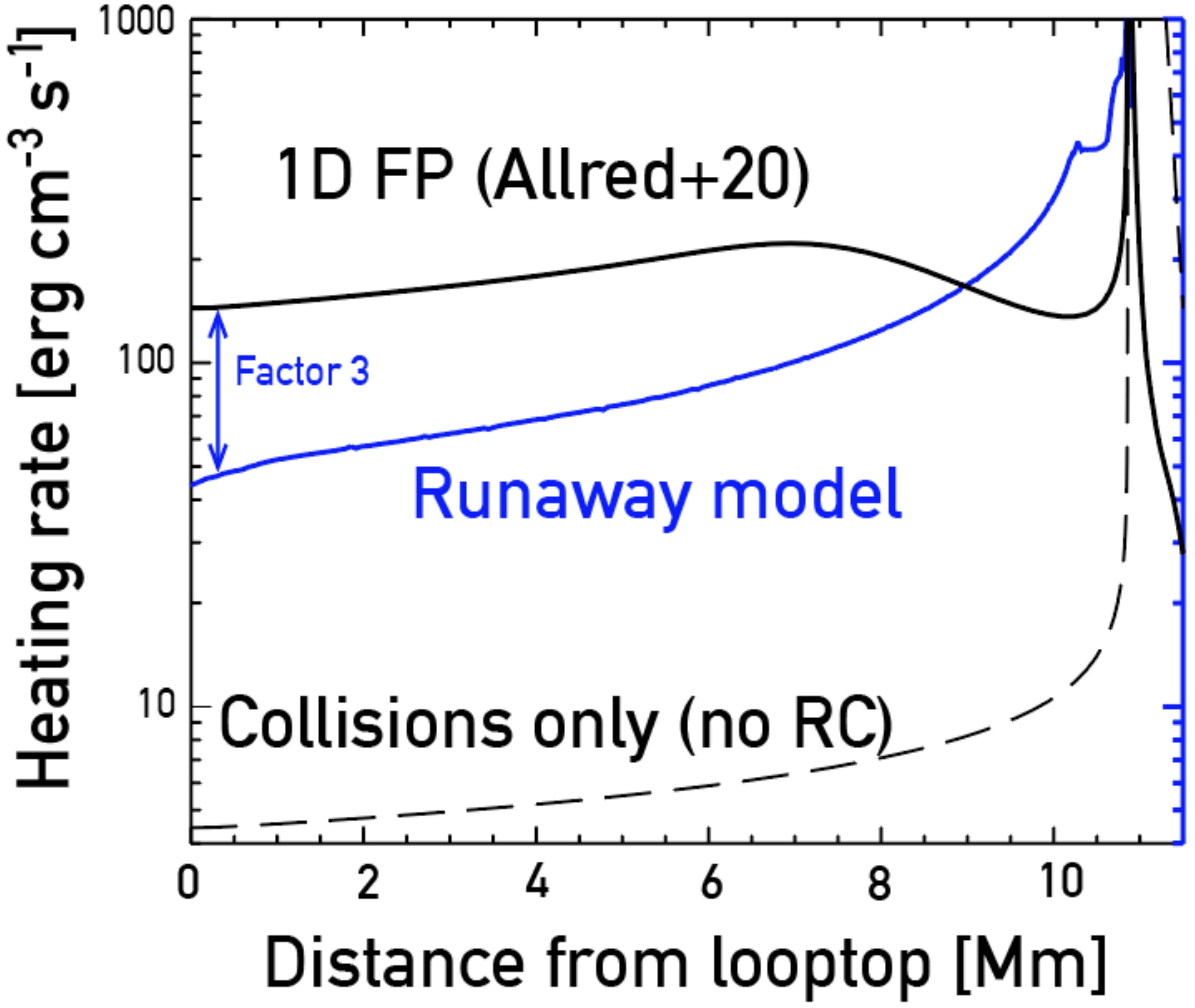




The heating in the chromosphere is overestimated when return currents are not considered

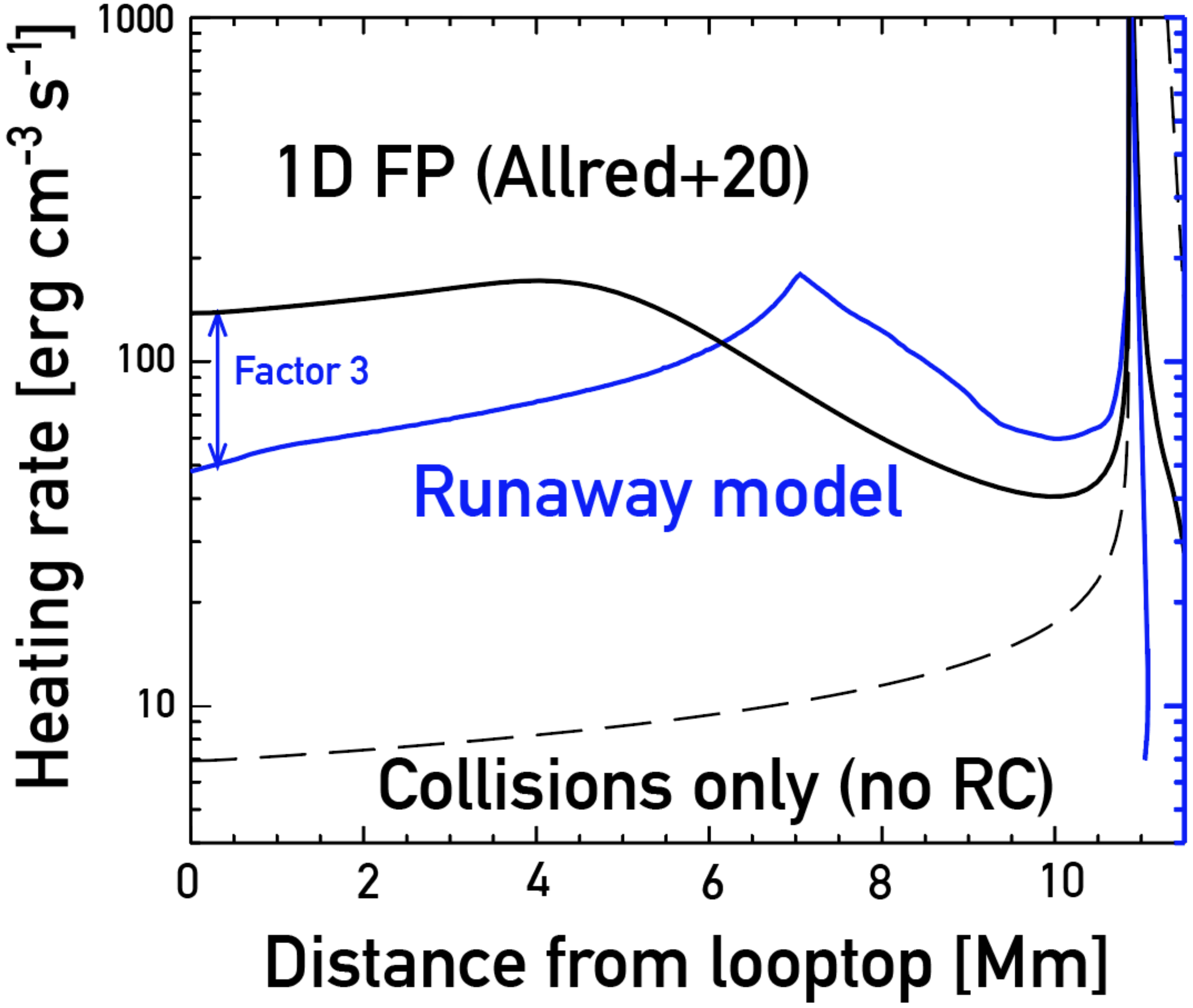
RETURN CURRENT LOSSES DOMINATE OVER COLLISIONS

Low-energy cutoff 25 keV



Same parameters (number flux density)

Except low-energy cutoff 15 keV



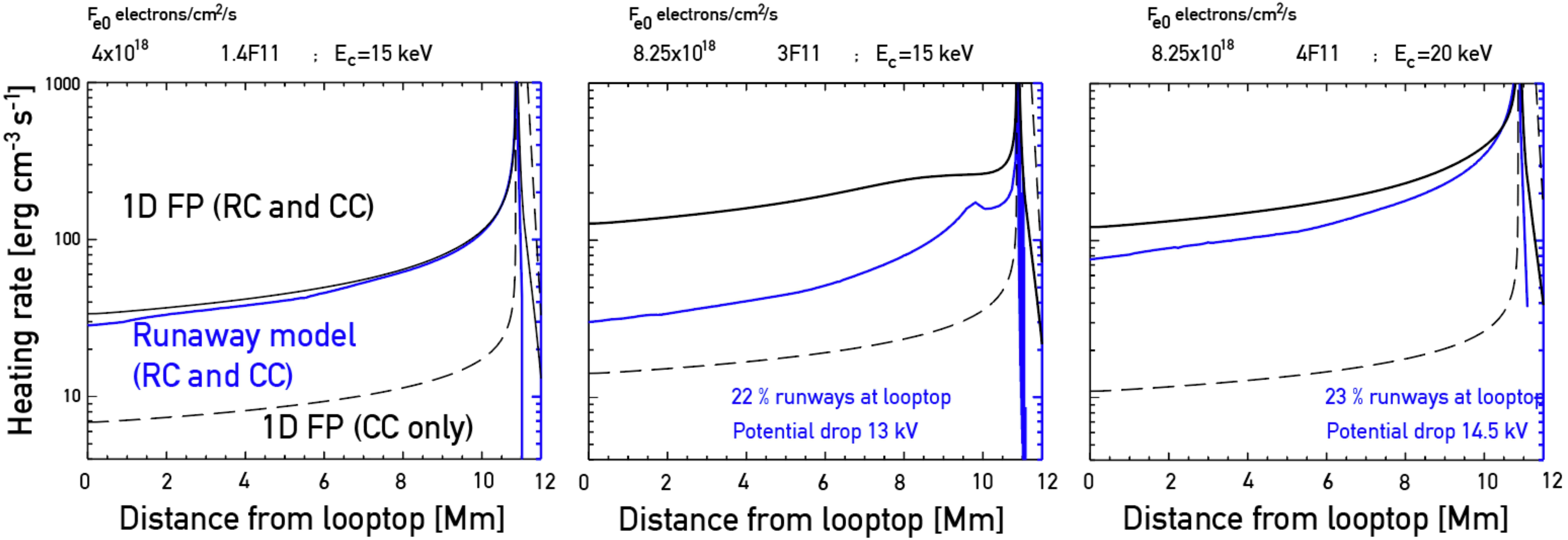
Return currents cannot be neglected

Even when considering heating reduction due to presence of runaways

Lower low-energy cutoff results in thermalization of more beam electrons in the corona=>reduced electron flux into chromosphere

IN HOTTER PLASMAS RETURN CURRENTS ARE STILL SIGNIFICANT

Same atmosphere with apex temperature 10 MK, same spectral index δ=4



Same beam parameters as example 1 but hotter atmosphere

RC significant but runaways negligible

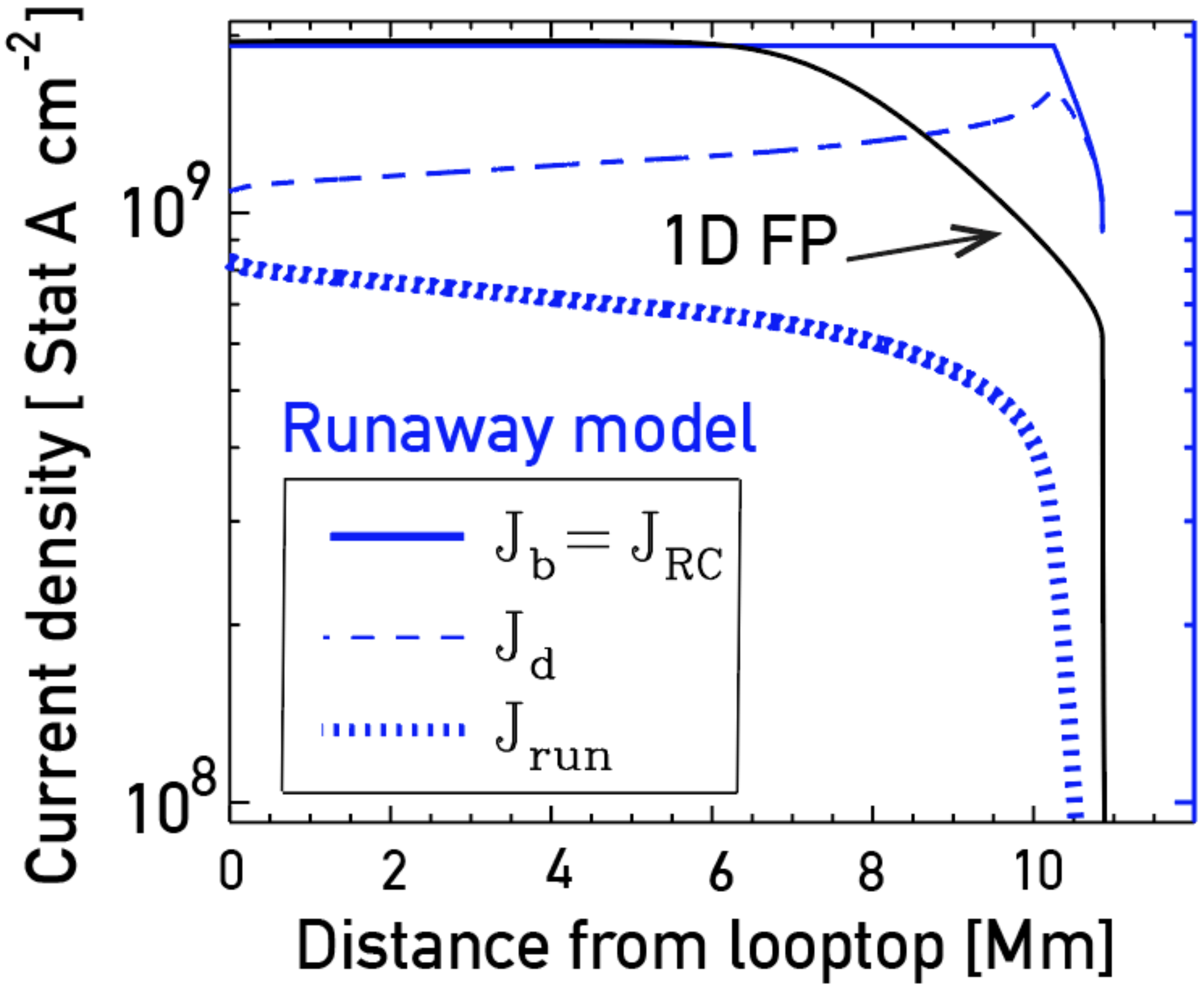
Higher injected flux density compared to example on left

Higher injected flux=> higher runaways and higher reduction of heating +Coulomb collisions contribute to reducing the heating especially in runaway case

Same injected flux density compared to example in the middle, higher low-energy cutoff

Beam electrons thermalized below transition region

RETURN CURRENT AFFECTS ACCELERATION REGION AND CHROMOSPHERE



INPUT PARAMETERS

T=3.2 MK $\quad n_e = 7.5 \times 10^9 cm^{-3}$

$F_{e0} = 4 \times 10^{18} e^- cm^{-2} s^{-1} \quad ; \quad 2.4F11$

$E_{c0} = 25$ keV $\quad \delta = 4$

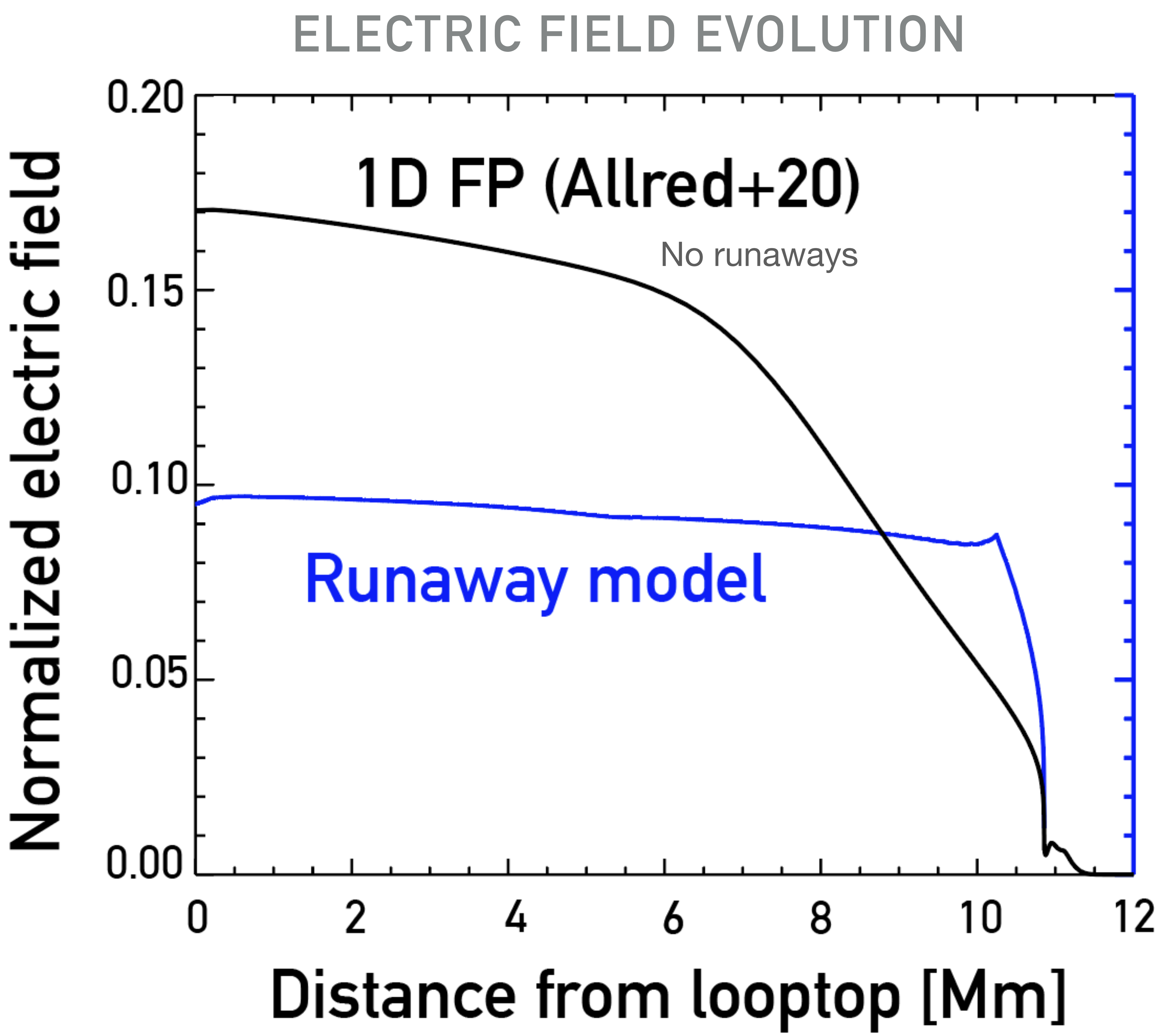
Main implications

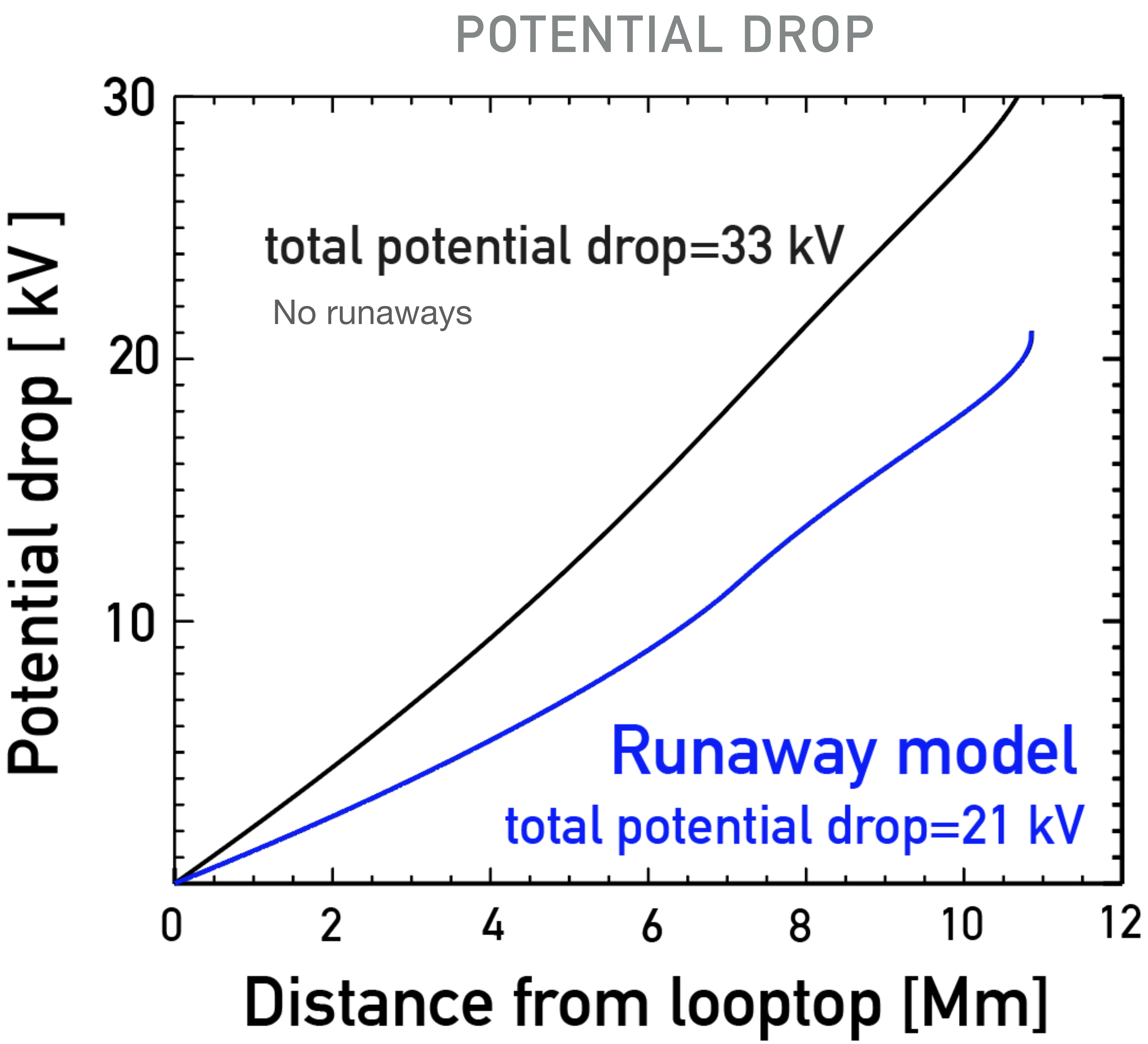
(1) 43% of flux returning to acceleration region is suprathermal

(2) Electron flux injected into chromosphere reduced due to thermalization by the return current

(3) Corona is a "warm target" because of return current losses

EXAMPLE 1: ELECTRIC FIELD & POTENTIAL DROP SPATIAL EVOLUTION





Energy of runaway electrons at looptop (gain of 21 keV) >> thermal energy

Electrons returning to the acceleration region are already suprathermal=> further accelerated to keep acceleration ongoing

SUMMARY

arXiv link: https://arxiv.org/pdf/2103.13999.pdf

THERMAL RESPONSE

(1) The corona is heated faster and to higher energies

(2) The chromosphere is heated slower and to lower energies

(3) Neglecting return currents overestimates injected electrons into chromosphere and accelerated electron flux densities

ELECTRON BEAM ACCELERATION

(1) When runaways are significant, they provide suprathermal particles which can be accelerated to even higher energies in the original acceleration region

(2) Runaways can have energies ~10-30 keV (i.e, lower but same order of magnitude as accelerated electrons)>> thermal energies

(3) Runaway electrons can be tens of % of the flux returning to acceleration region

Next: Develop a model for any electric field magnitude compared to the Dreicer field

Include pitch-angle dependence

Calculate the thermal response

Check out the papers

Runaway paper

https://arxiv.org/pdf/2103.13999.pdf

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Role of suprathermal runaway electrons returning to the acceleration region in solar flares

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ABSTRACT

During solar flares, a large flux of energetic electrons propagate from the tops of reconnecting magnetic flux tubes toward the lower atmosphere. Over the course of the electrons' transport, a co-spatial counter-streaming return current is induced, thereby balancing the current density. In response to the return current electric field, a fraction of the ambient electrons will be accelerated into the runaway regime. However, models describing the accelerated electron beam/return-current system have generally failed to take these suprathermal runaway electrons into account self-consistently. We develop a model in which an accelerated electron beam drives a steady-state, sub-Dreicer co-spatial return-current electric field, which locally balances the direct beam current and freely accelerates a fraction of background (return-current) electrons. The model is self-consistent, i.e., the electric field induced by the co-evolution of the direct beam and the runaway current is considered. We find that (1) the return current electric field can return a significant number of suprathermal electrons to the acceleration region, where they can be further accelerated to higher energies, runaway electrons can be a few tens of percent of the return current flux returning to the nonthermal beam's acceleration region, (2) the energy gain of the suprathermal electrons can be up to 10 – 35 keV, (3) the heating rate in the corona can be reduced by an order of magnitude in comparison to models which neglect the runaway component. The results depend on the injected beam flux density, the temperature and density of the background plasma.

Keywords: Sun: flares — Sun: X-rays, gamma rays- Runaway electrons

1. INTRODUCTION

Co-spatial return currents (RCs) have been proposed to balance the electron flux required to explain the observed X-ray bremsstrahlung emission in solar flares (Hoyng et al. 1976). The bremsstrahlung emission above ~ 20 keV provides the most direct link to the nonthermal electron distribution. The RC locally neutralizes the charge build-up and cancels the magnetic field induced by the beam of accelerated electrons, thereby solving the so-called "number problem" (Benz 2008), and the associated current stability problem (Bennett 1934, 1955). The electric field that drives the RC produces a potential drop between the acceleration region in the corona and the flare-loop footpoints, and decelerates the electrons in the beam. There is growing observational evidence that the acceleration region is located in the outflow jets away from the reconnection region (e.g., Sui & Holman 2003; Gary et al. 2018; Chen et al. 2018, 2021). The potential drop can be detected by a flattening in the X-ray spectrum at low energies, in the deka-keV range (Holman 2012; Zharkova & Gordovskyy 2006). The electric field accelerates the thermal background electrons that then undergo collisions to produce a drifting Maxwellian (Knight & Sturrock 1977; Spicer & Sudan 1984; Emslie 1980; Larosa & Emslie 1989; Zharkova et al. 1995; Zharkova & Gordovskyy 2005, 2006; Alexander & Daou 2007; Codispoti et al. 2013). However, the electrons for which the electrical

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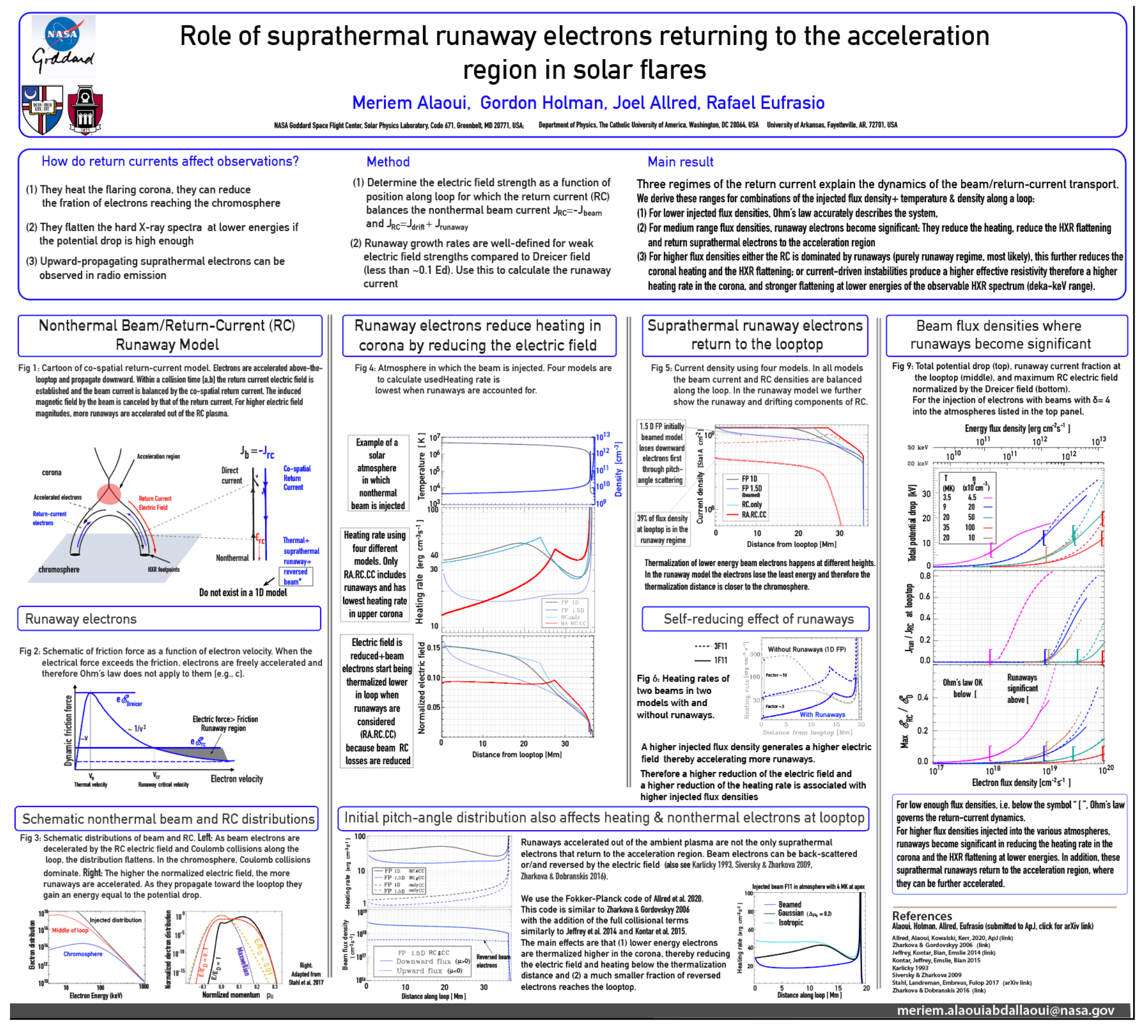
SolFER meeting poster on runaway electrons

https://hesperia.gsfc.nasa.gov/collaborate/malaouia/public_html/alaoui-44.pdf



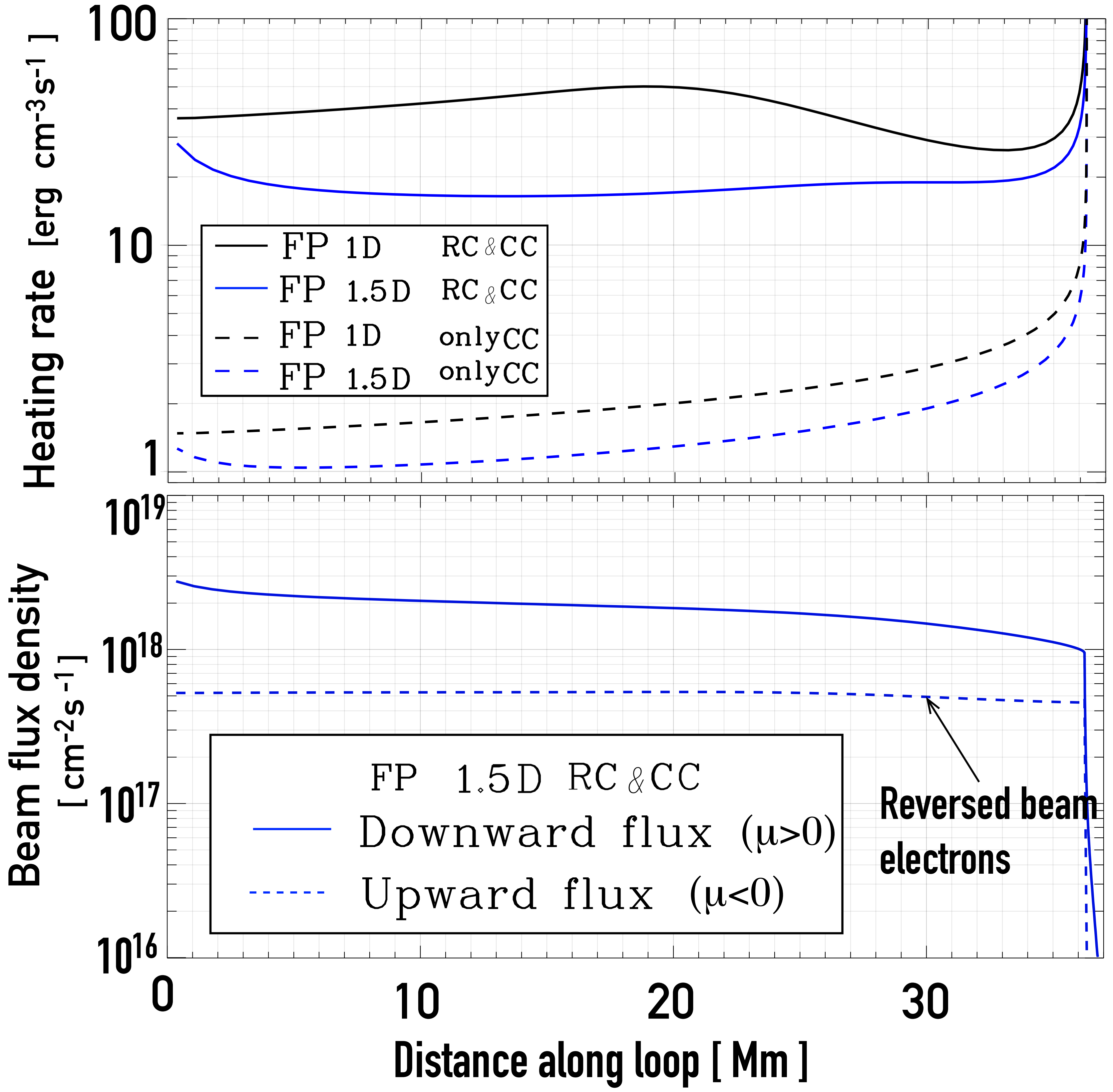
Also check FP paper: Allred et al. 2020

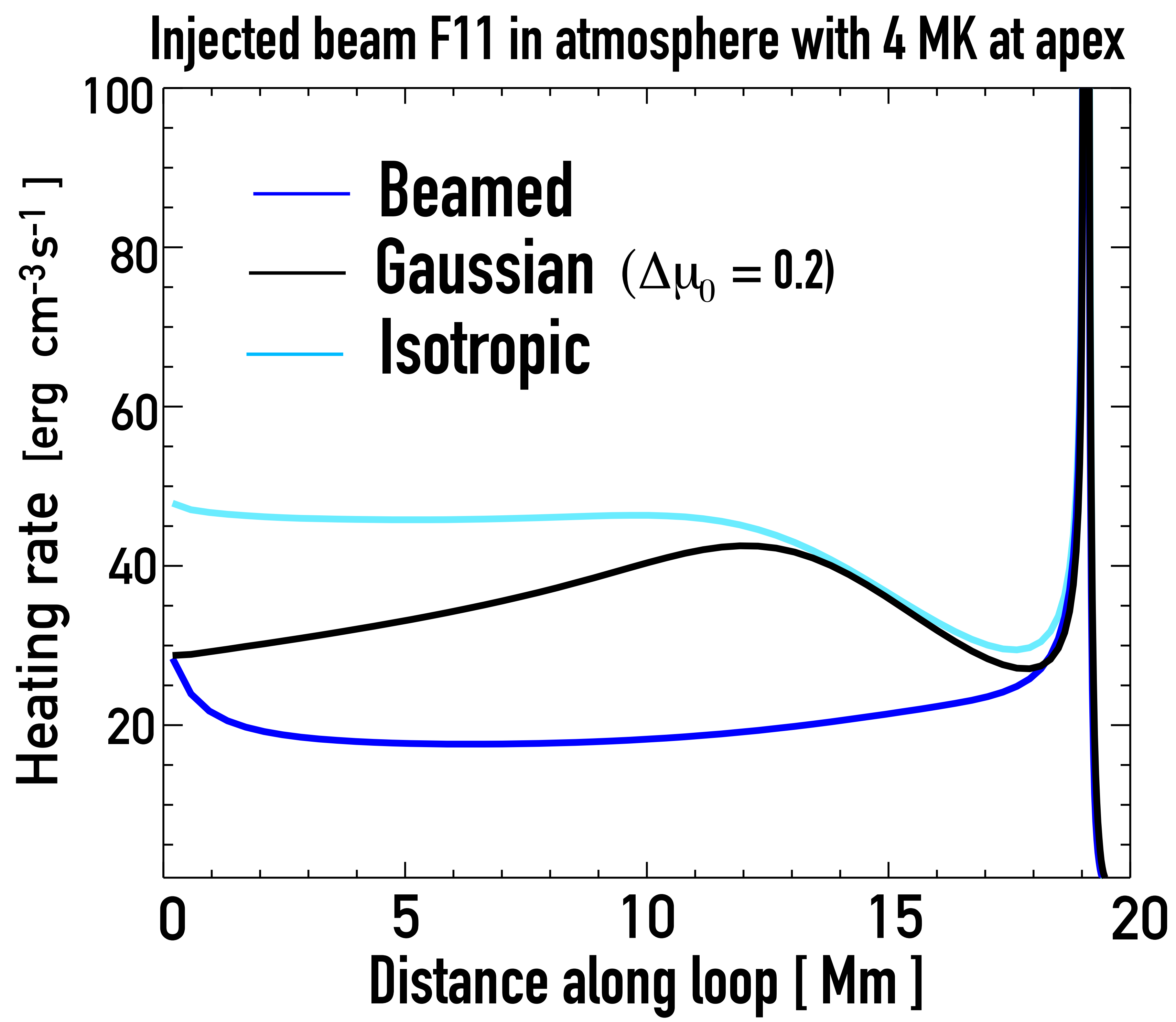
https://iopscience.iop.org/article/10.3847/1538-4357/abb239/pdf

EXTRA SLIDE:FIVE ATMOSPHERES WITH CONSTANT CORONAL TEMPERATURE AND DENSITY

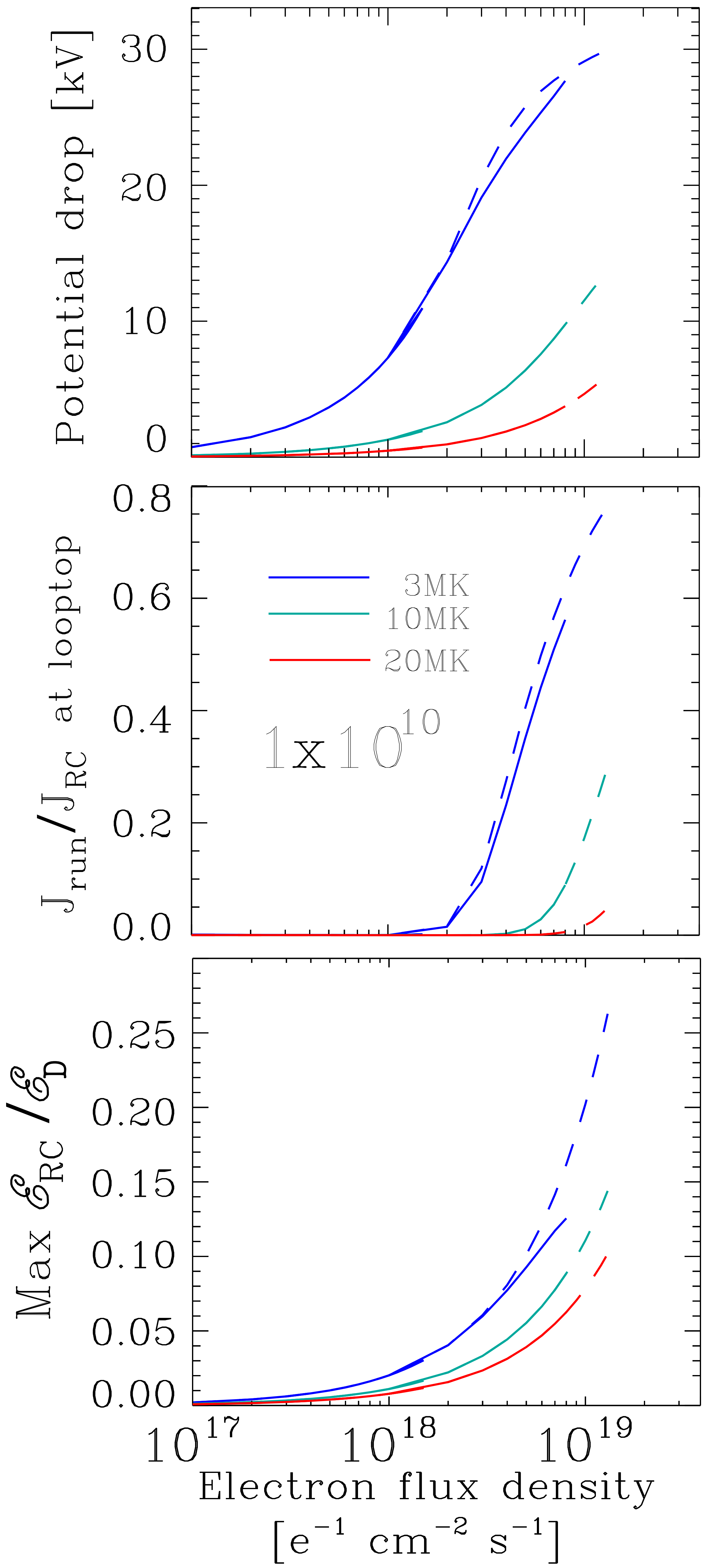
EXTRA SLIDE: INITIAL PITCH-ANGLE DISTRIBUTION AFFECTS THE HEATING

Calculations using Allred et al. 2020





EXTRA SLIDE



Constant temperature
and density in 20 Mm coronal loops

Solid lines: 20 keV
Dashed lines: 50 keV